Top quark properties at (linear) e+e- colliders

Top EW couplings, G. Durieux et al., JHEP 1912, 098
Top mass, M. Boronat et al., arXiv:1912.01275

E. Fullana, P. Gomis, M. Perelló, M. Vos

IFIC, CSIC/UV, Valencia, Spain

DESY Hamburg, 21/02/2020

Based on work with A. Irles, Pöschl, Richard and I. García, CLICdp and ILD

Theory: A. Hoang, V. Mateu, A. Widl, & G. Durieux, C. Zhang

ongoing work with S. Jung & J. Tian and others

The top quark

One of two SM particles to escape scrutiny at LEP

→ precise constraints on top (EW) couplings are missing

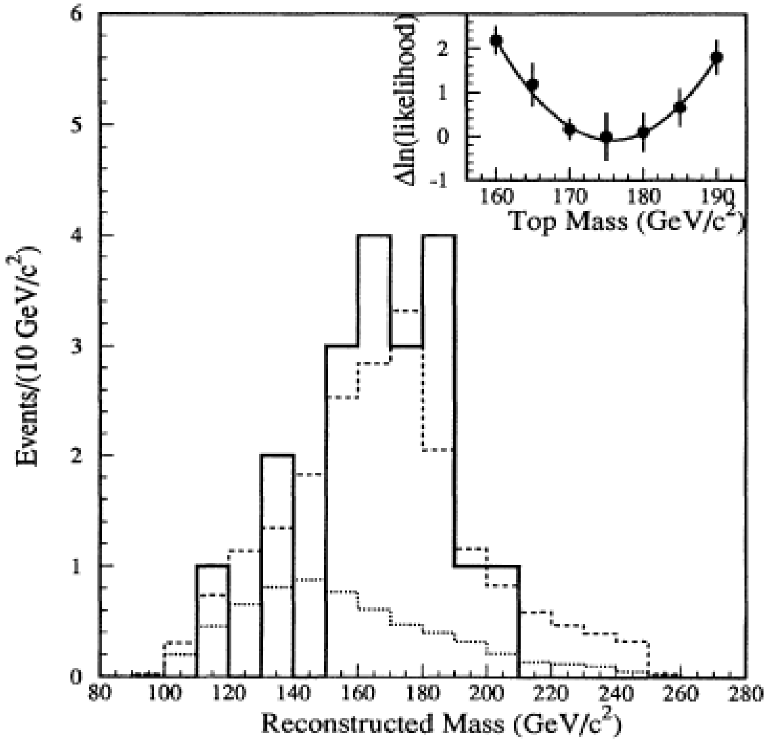
The SM particle with the closest connection to the Higgs

→ top Yukawa coupling is a key target of HEP

Somewhat forgotten in our excitement about the Higgs

→ but a necessary target of future e+e- facilities

Top quark mass



If top physics should ever get boring,
just ask a random group of theorists
“does the direct mass measurement yield the pole mass?”

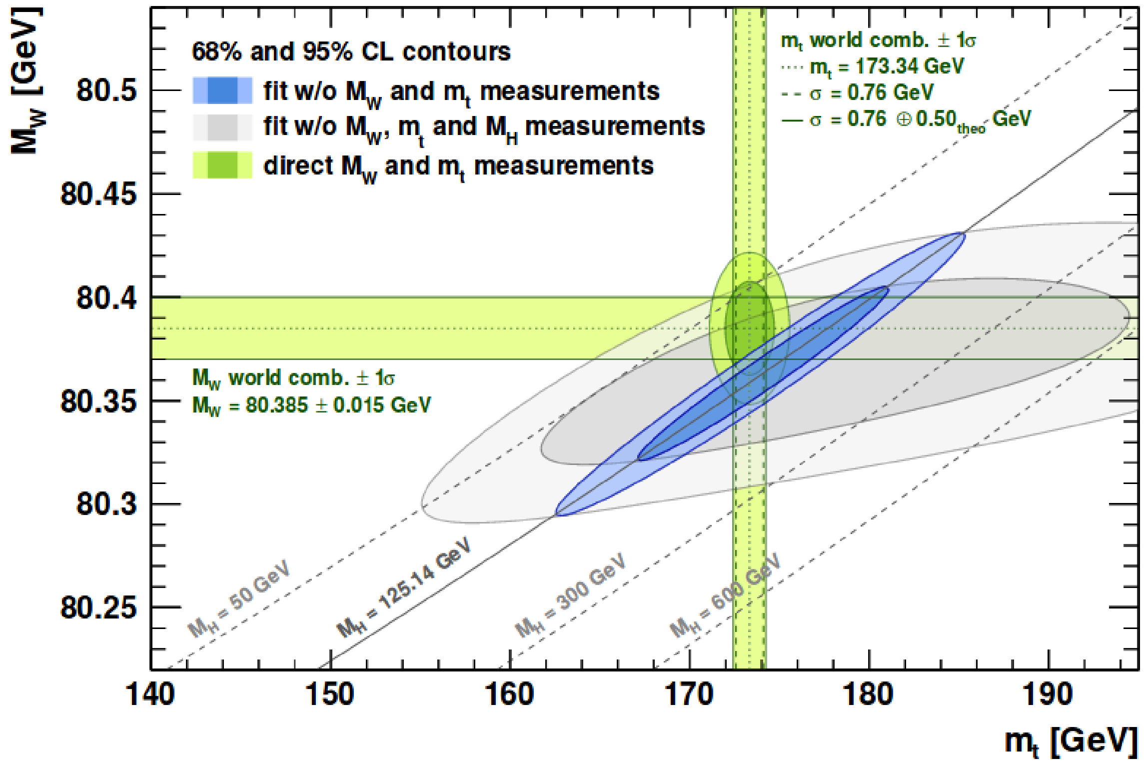
The top quark mass and the EW fit

arXiv:1407.3792

New e^+e^- machines can **take the EW fit to next level**

TLEP physics case, arXiv:1308.6176
Snowmass EW, arXiv:1310.6708

Precise top quark mass measurement is a crucial ingredient to "closure test" of the Standard model.



Top quark mass measurements at the LHC

Direct mass: m_{MC} = 172.9 ± 0.4 GeV
From cross-section: m_{pole} = 173.1 ± 0.9 GeV

PDG world average

m = 171.1 ± 1.2 GeV (ATLAS tt+jet differential)
m = 170.5 ± 0.8 GeV (CMS 3D differential)

Interpretation of direct top mass measurement under active development

Calibrate MC mass parameter: *Hoang et al., PRL117*
Parton shower analytics: *Hoang et al., arXiv:1807.06617*
Improve MC precision: *Nason et al., arXiv:1607.04538, arXiv:1801.03944*
Renormalon ambiguity: *Beneke et al., arXiv:1605.03609*

See seminar by André Hoang, DESY, last Monday:
https://indico.desy.de/indico/event/25314/contribution/2/material/slides/0.pdf

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Progress at the LHC: top quark mass revisited

Projection of exp. uncertainties

HL-LHC, hep-ph/0204087: "uncertainty (dominated by systematics) of ~ 1 GeV […]"
"more data offer no obvious improvement."

Snowmass, arXiv:1310.0799: *"mass extraction with uncertainty as low as 500-600 MeV"*

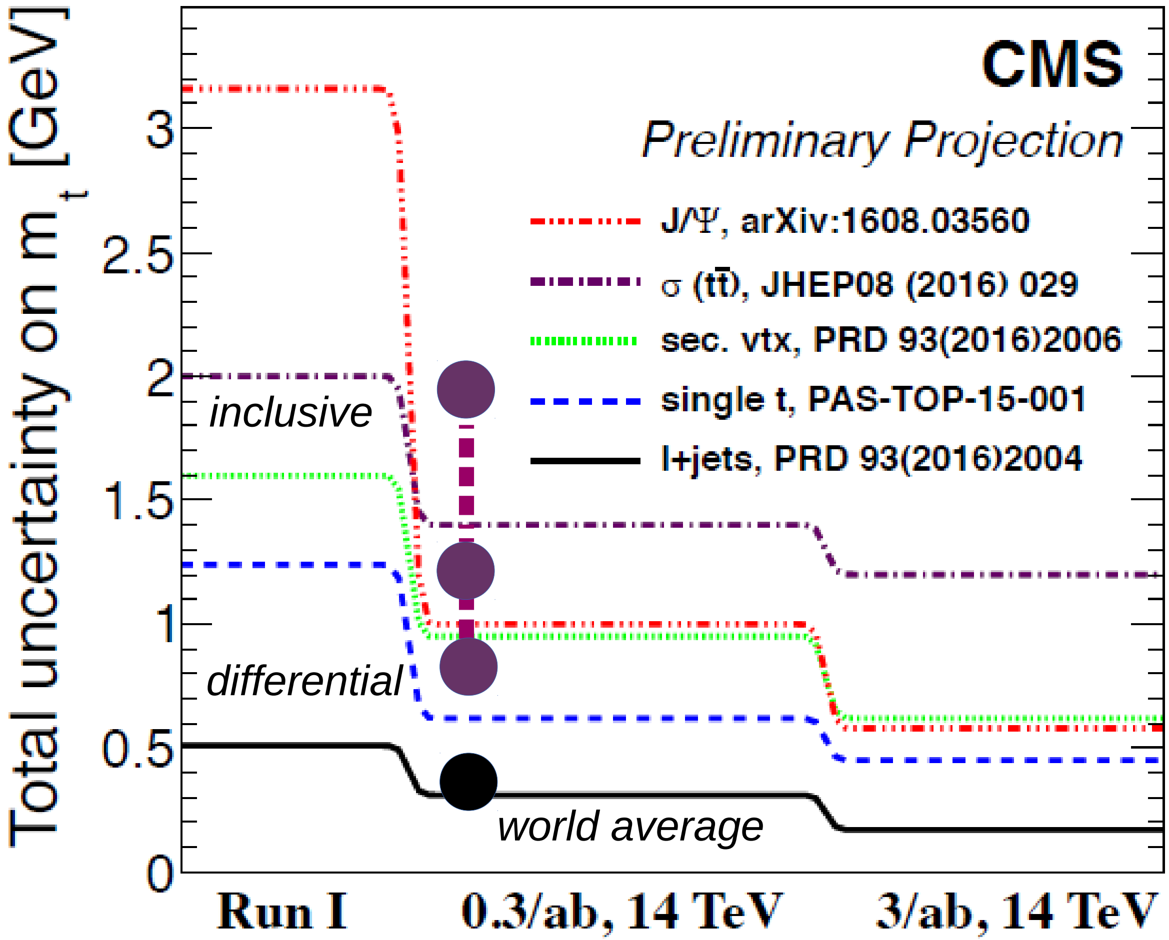
CMS-FTR-13-017-PAS: "200 MeV [under] optimistic but not unrealistic assumptions."

CMS-DP-2016-064: "Conventional methods [...] ultimate relative precision below 0.1%."

We are definitely more ambitious than before the start of the LHC

Progress at the LHC: top quark mass revisited

Projection of experimental uncertainties



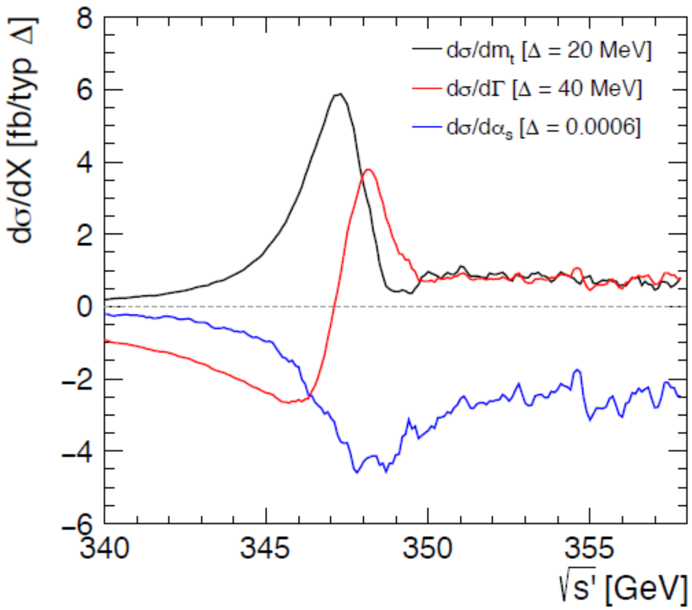
Projection of theory uncertainties

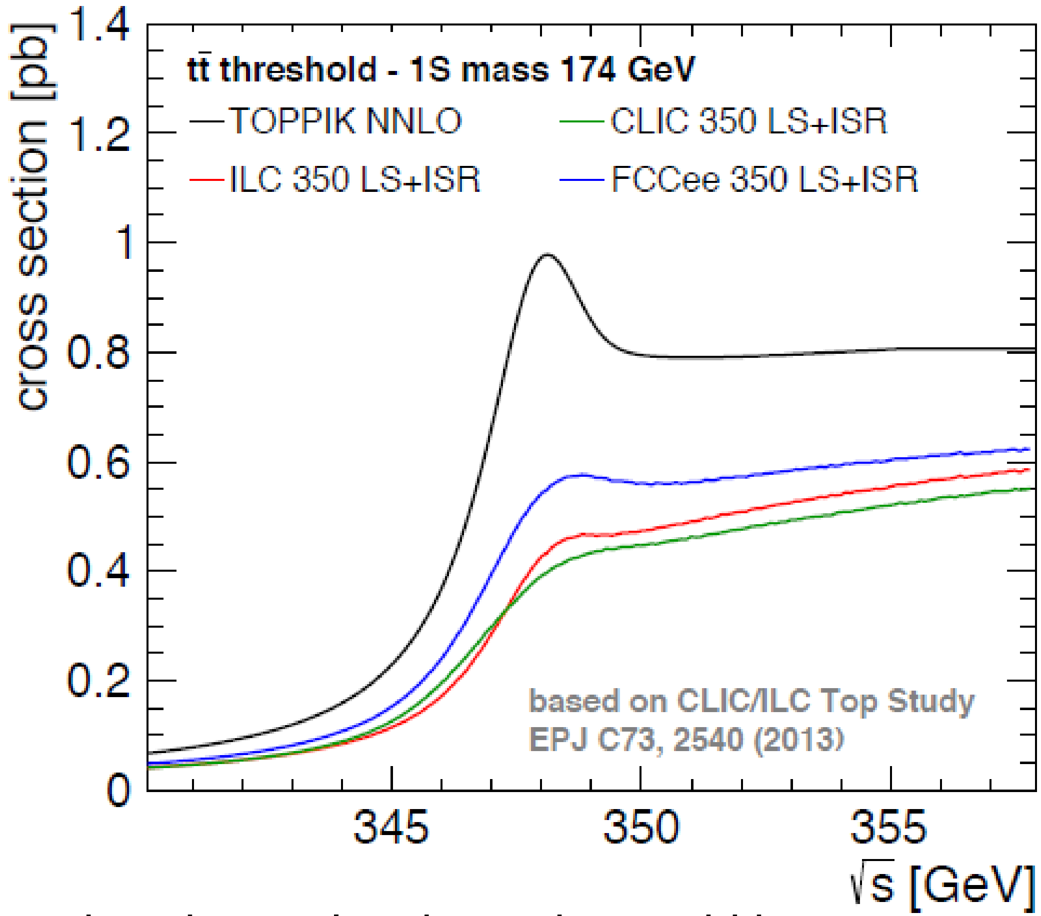
HL-LHC, arXiv:1902.04070: “In summary, from a theoretical point of view, much work is still needed to put the top mass measurements at the HL-LHC on a solid ground […] in spite of the many challenges, one can expect that a theoretical precision matching the foreseeable experimental errors for top mass measurements at the HL-HLC can be achieved.”

Top quark mass from e^+e^- threshold scan

Threshold shape reveals the top quark mass

Kuhn, Acta Phys.Polon. B12 (1981)





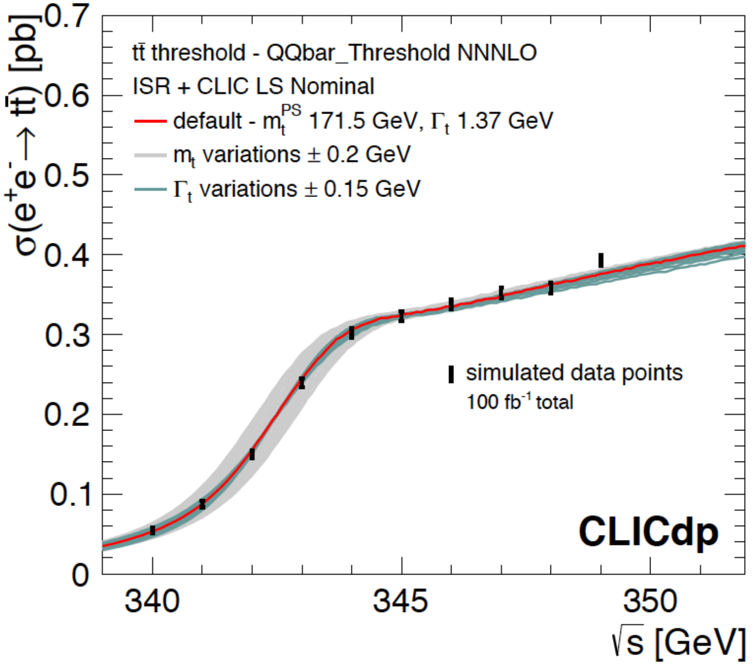
Line shape also depends on width,
Normalization sensitive to α_s and y_t

Detailed estimates of the precision in multi-parameter fits

Martinez, Miquel, EPJ C27, 49 (2003), Horiguchi et al., arXiv:1310.0563, Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

Top quark mass from e^+e^- threshold scan

Source	Uncertainty	Comment
Stat.	~20 MeV	*100 fb^{-1}*
Scale	~40 MeV	*N^3LO QCD, arXiv:1506.06864*
Parametric	~30 MeV	*α_s world average, arXiv:1604.08122*
Exp. syst	25-50 MeV	*including LS, arXiv:1309.0372*



The threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

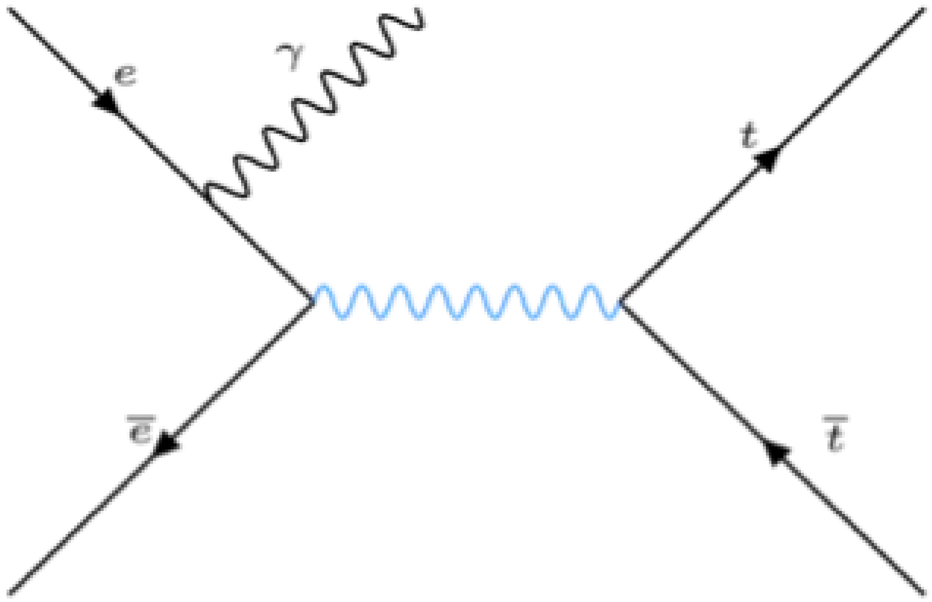
Marquard et al., PRL114, arXiv:1502.01030

A very competitive top quark mass measurement:

$\Delta m_t \sim 50$ MeV (= 3×10^{-4}, cf. $\Delta \mathbf{m_b}$ **~1%**)

Note: this is a prospect, not a target! ~independent of machine design and parameters.

Top quark mass from radiative events

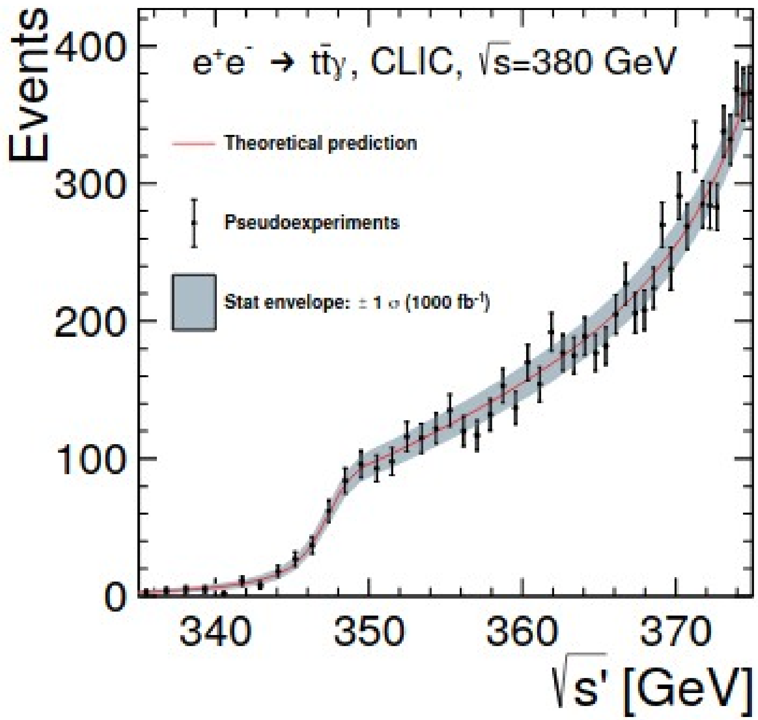


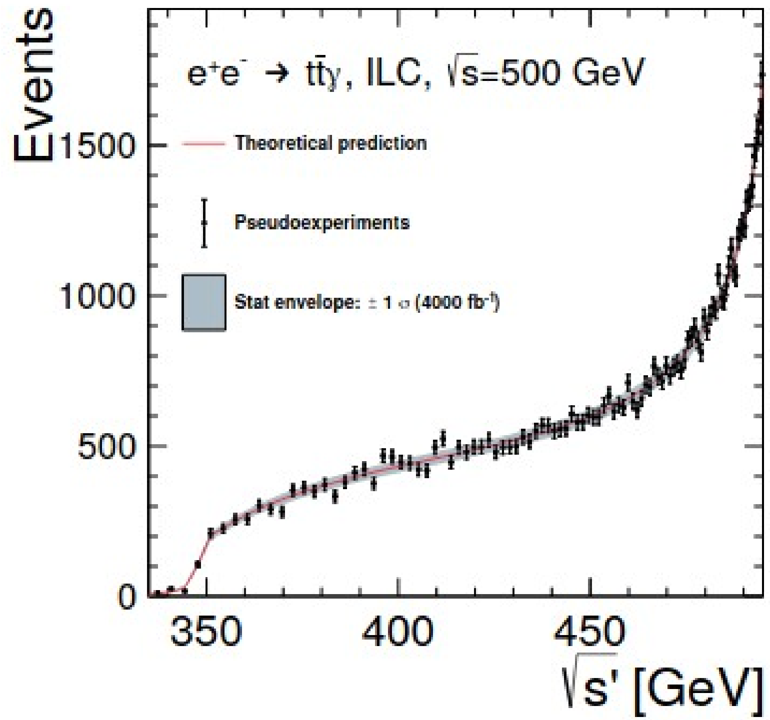
Alternative method for standard run

CLIC: 1 ab^{-1} at 380 GeV
ILC: 4 ab^{-1} at 500 GeV

ISR photon reduces effective √s (return-to-threshold)
Matched NNLO+NNLL calculation, Hoang, Mateu, Widl
Factorize ISR and e+e- → tt production

Top quark mass from radiative events





Radiative "return to threshold" in e+e- → ttγ events

Threshold shape accessible by measuring photon energy

2/3 of photons escape in beam pipe

use visible energy or extend forward coverage

Luminosity spectrum folded in explicitly

Top quark mass from radiative events

Ph.D. Pablo Gomis, UV, jan. 2020

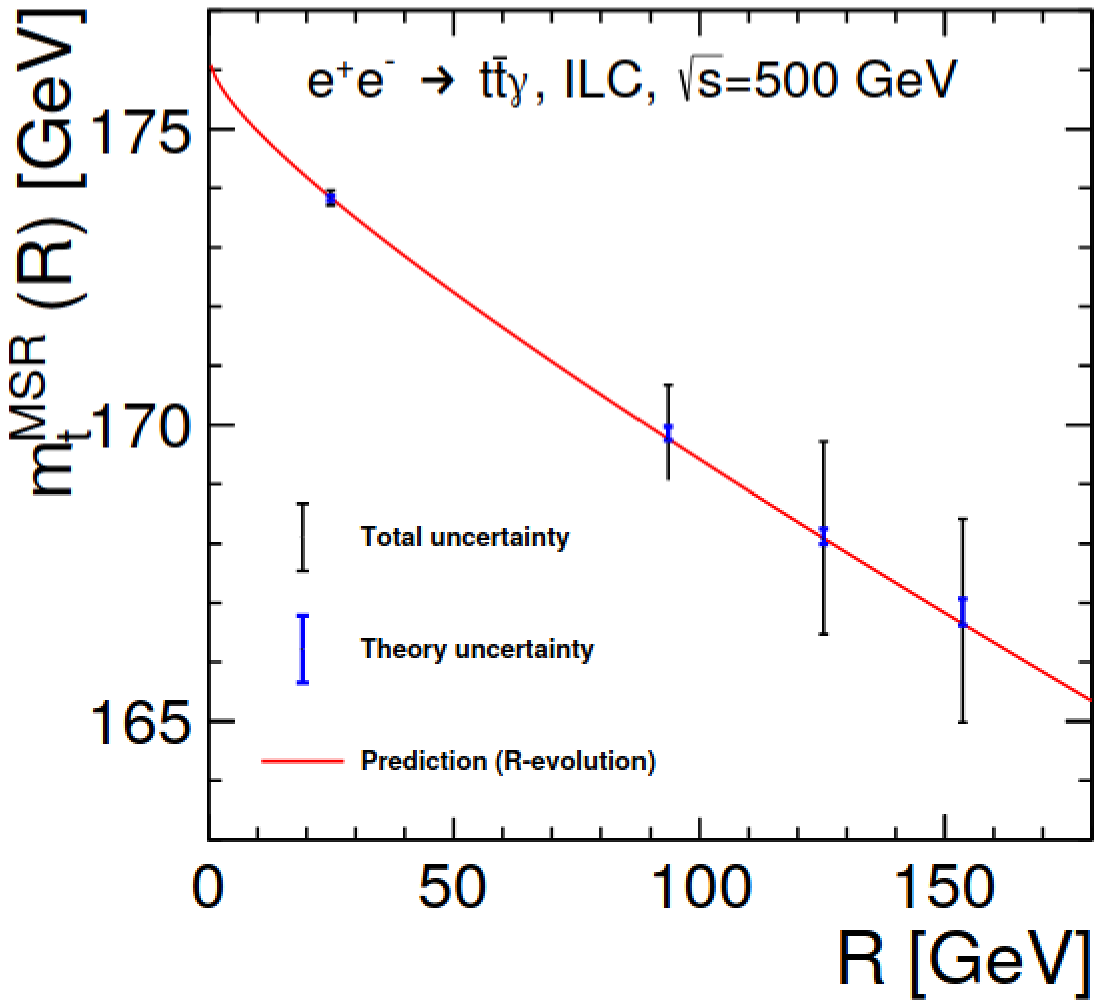
cms energy	CLIC, $\sqrt{s} = 380\,\text{GeV}$		ILC, $\sqrt{s} = 500\,\text{GeV}$	
luminosity $[\text{fb}^{-1}]$	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

Extract short-distance MSR mass with rigorous interpretation and competitive precision:

CLIC380 (1/ab): 50 MeV (theory), 110 MeV total

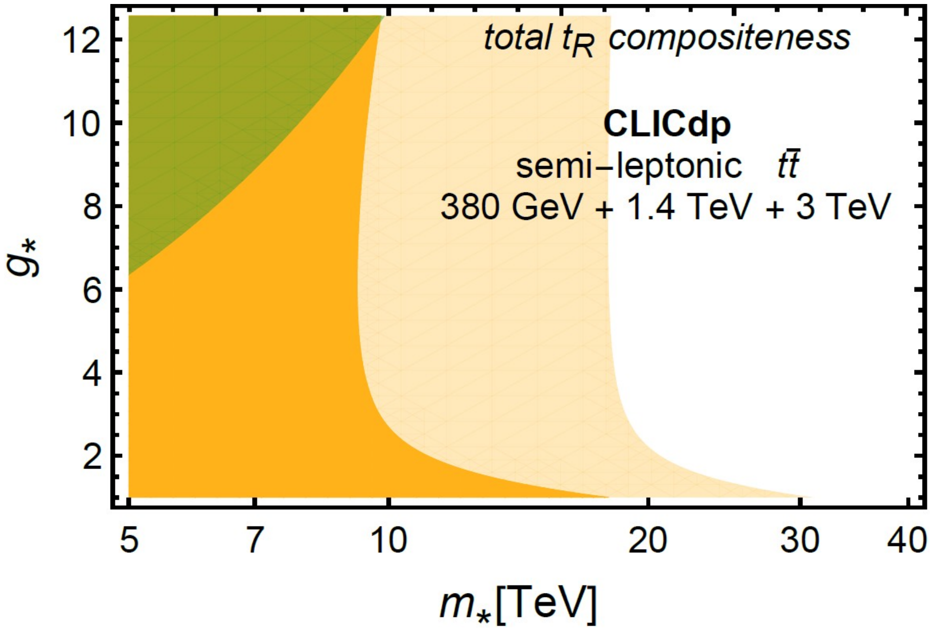
ILC500 (4/ab): 50 MeV (theory), 150 MeV total

Top quark mass from radiative events



5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone

EW couplings
of the top quark



One of those interesting corners of the SM:

Current constraints are weak; sizeable deviations from BSM are possible

Richard, arXiv:1403.2893, Durieux & Matsedonskiy, CLIC new physics yellow report

Top EW couplings at the LHC

Neutral current: ttZ, ttγ associated production (tZ, tγ)

→ processes "discovered", cross section measurements 10-20%

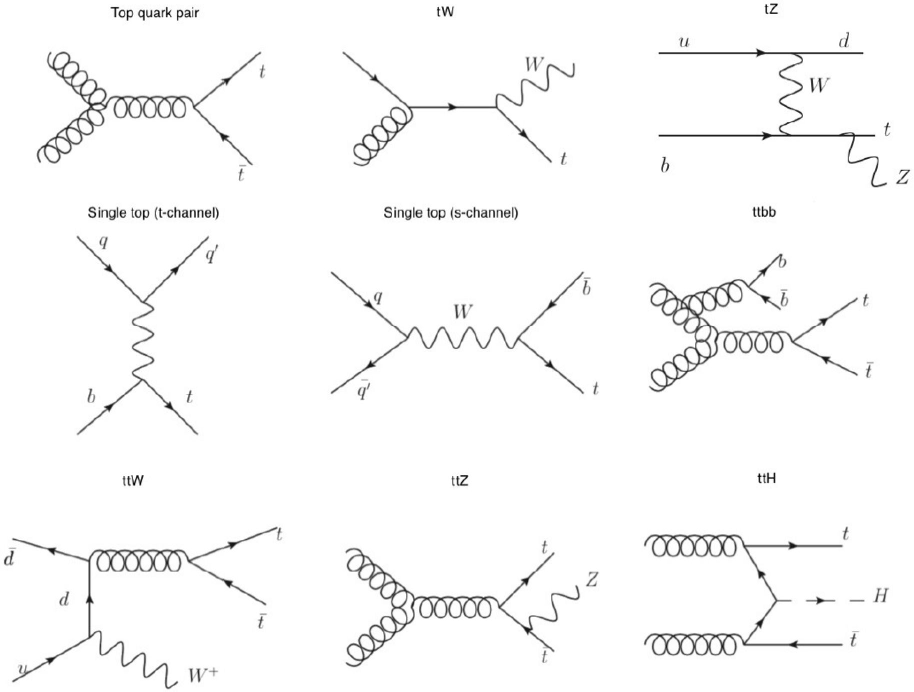
Charged current: single top production, top decay observables

→ precision top physics at the LHC

Yukawa interaction: ttH (tH) production

→ observed in 2018

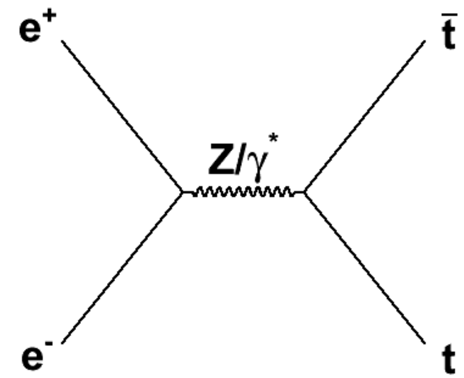
ATLAS, PLB 784, 173-191 (2018)
CMS, PRL 120, 231801 (2018)



Current status:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Prospect studies:
Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911
FCChh SM study, arXiv:1607.01831

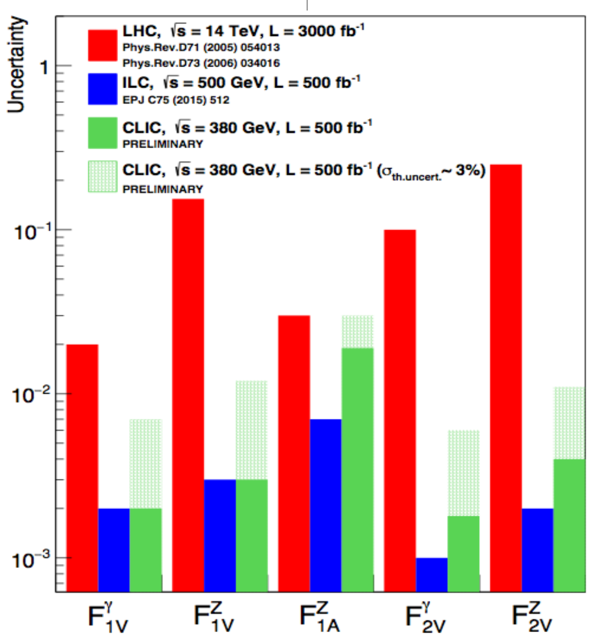
Top EW couplings at lepton colliders

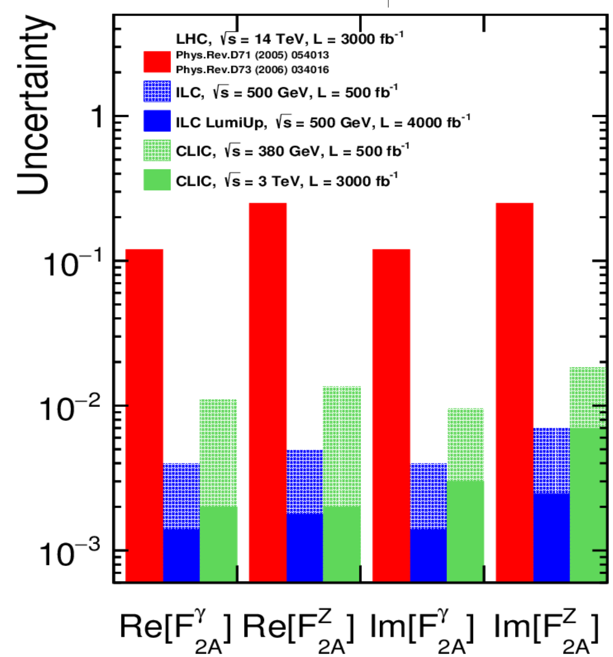


The best laboratory to test $\gamma t\bar{t}$ and $Zt\bar{t}$ vertices

FCC-ee, arXiv:1503.01325, 1509.09056
ILC di-lepton, arXiv:1503.04247

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$





Prospects for HL-LHC/ILC500/CLIC380

arXiv:1307.8102, arXiv:1505.0620

EFT interpretation

Quantify BSM sensitivity in a model-agnostic way with limits on anomalous D6 operator coefficients in Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

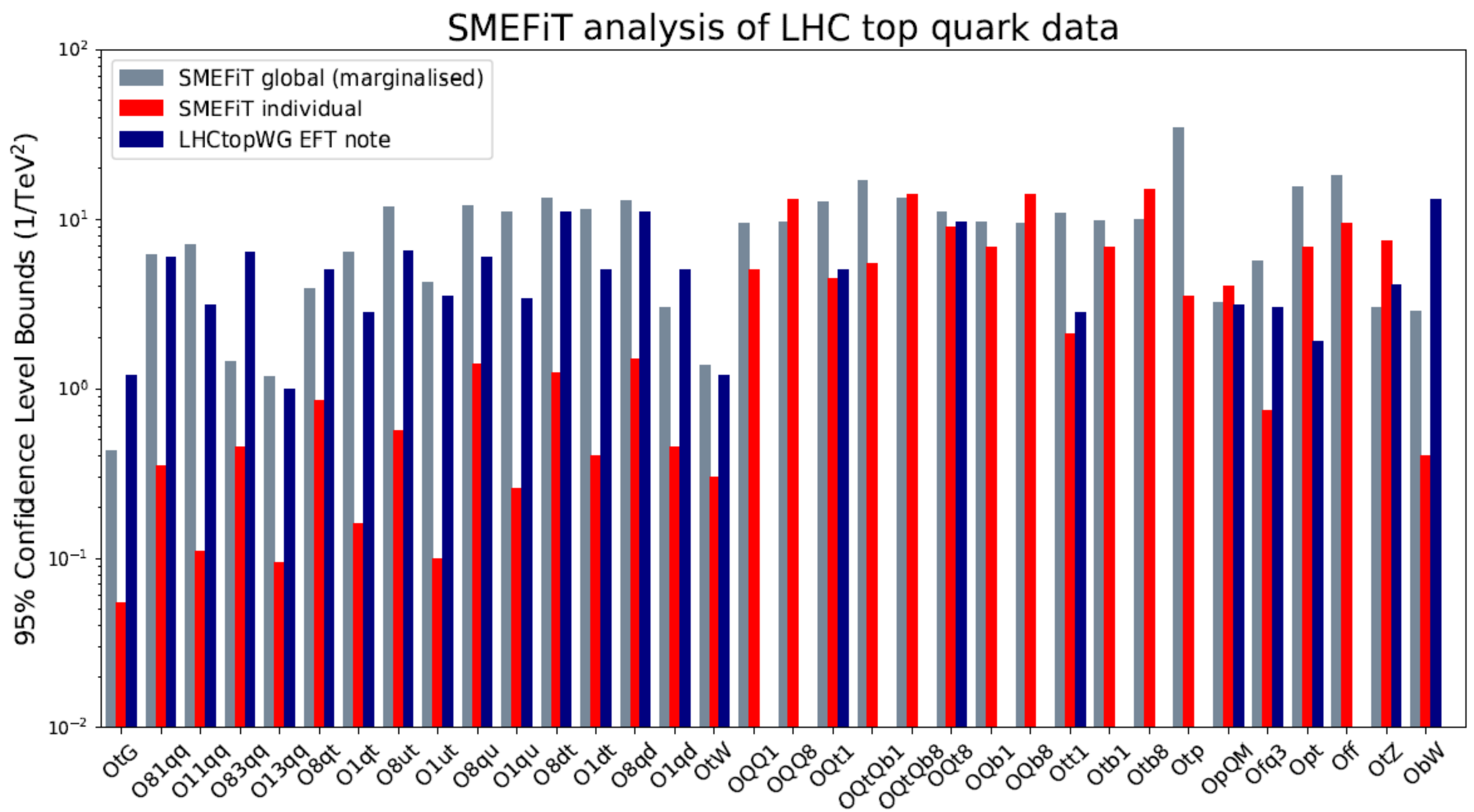
EFT analyses “by sector” are becoming the standard interpretation for LHC analyses.

Expected to evolve towards a “global” 59-parameter SM-EFT fit (under some flavour assumptions) in next decade

Very powerful benchmarking tool for future projects.

Global fit to the top sector

Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang, arXiv:1901.05965

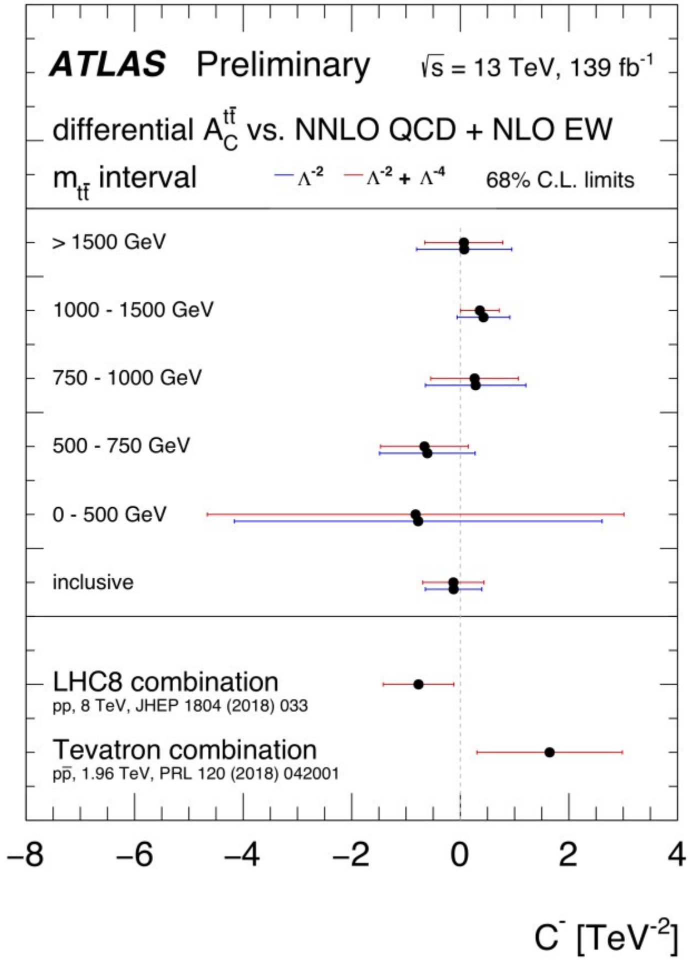


34 parameters, all LHC data (diff. x-sec for single and pair, associated prod., decay)
Top QCD : very good individual limits ~0.1, global limits O(1)
Top EW : poorer individual limits, typically O(several), first global results!

Global EFT fits

Effect of 4-fermion operators ~ E^2

Effect of 2-fermion operators ~ E^0



Hadron colliders: differential measurements

ATLAS-CONF-2019-025

Lepton colliders: multiple center-of-mass energies

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

Many other authors, for top Fiolhiais et al., arXiv:1206.1033

A simple fit

Identify an “isolated system” of top EW operators

$C_{t\phi}$ = modifies top Yukawa

$C^1_{\phi Q}$ = modifies left-handed coupling of top quark

$C^3_{\phi Q}$ = idem.

Shared with bottom quark → LEP constraints

$C_{\phi t}$ = modifies right-handed coupling of top quark

C_{tW} = top dipole moment

C_{tB} = idem.

$C_{\phi b}$ = bottom quark

C_{dW} = bottom quark dipole

Bottom quark operators: the prize to pay for including $e^+e^- \rightarrow b\bar{b}$ constraints

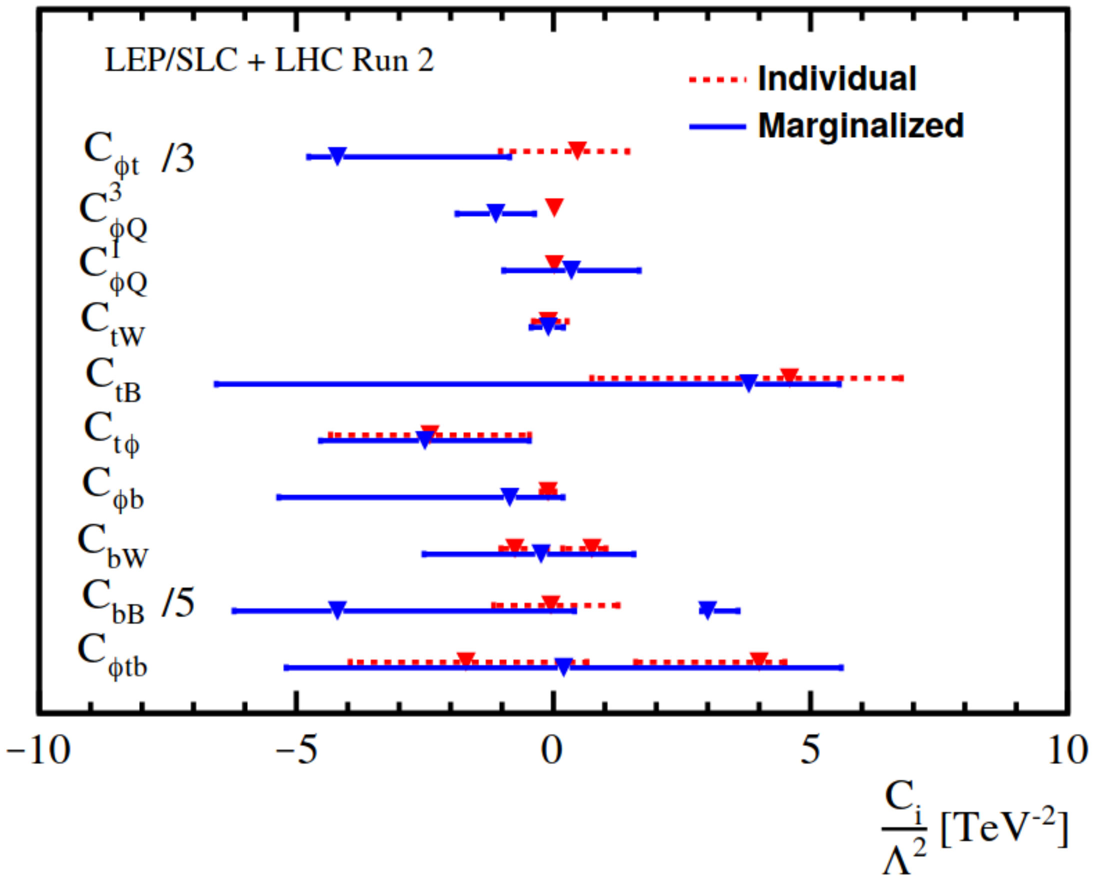
Does not include QCD operators, which are tightly constrained

Does not include $llt\bar{t}$ four-fermion operators, like (most) other analyses

Does not include CP-violating interactions, which can be constrained very well

Dedicated fit to top EW operators

Dedicated fit to top and bottom EW operators [M. Perelló et al.]



Current constraints are order(few TeV^{-1})

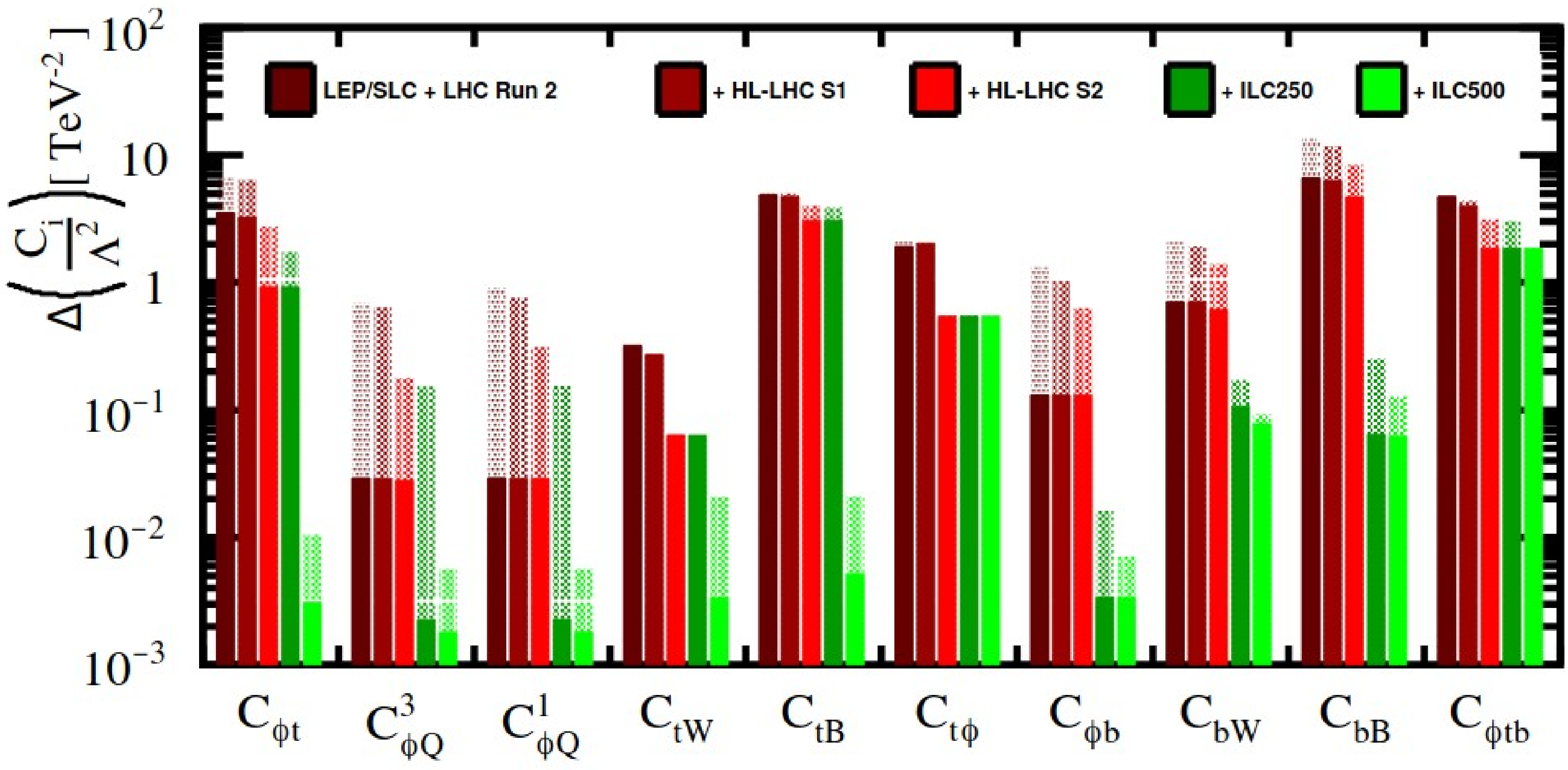
R^b, A_{FB} @ LEP/SLC

Associated ttX @ LHC

Single top & top decay

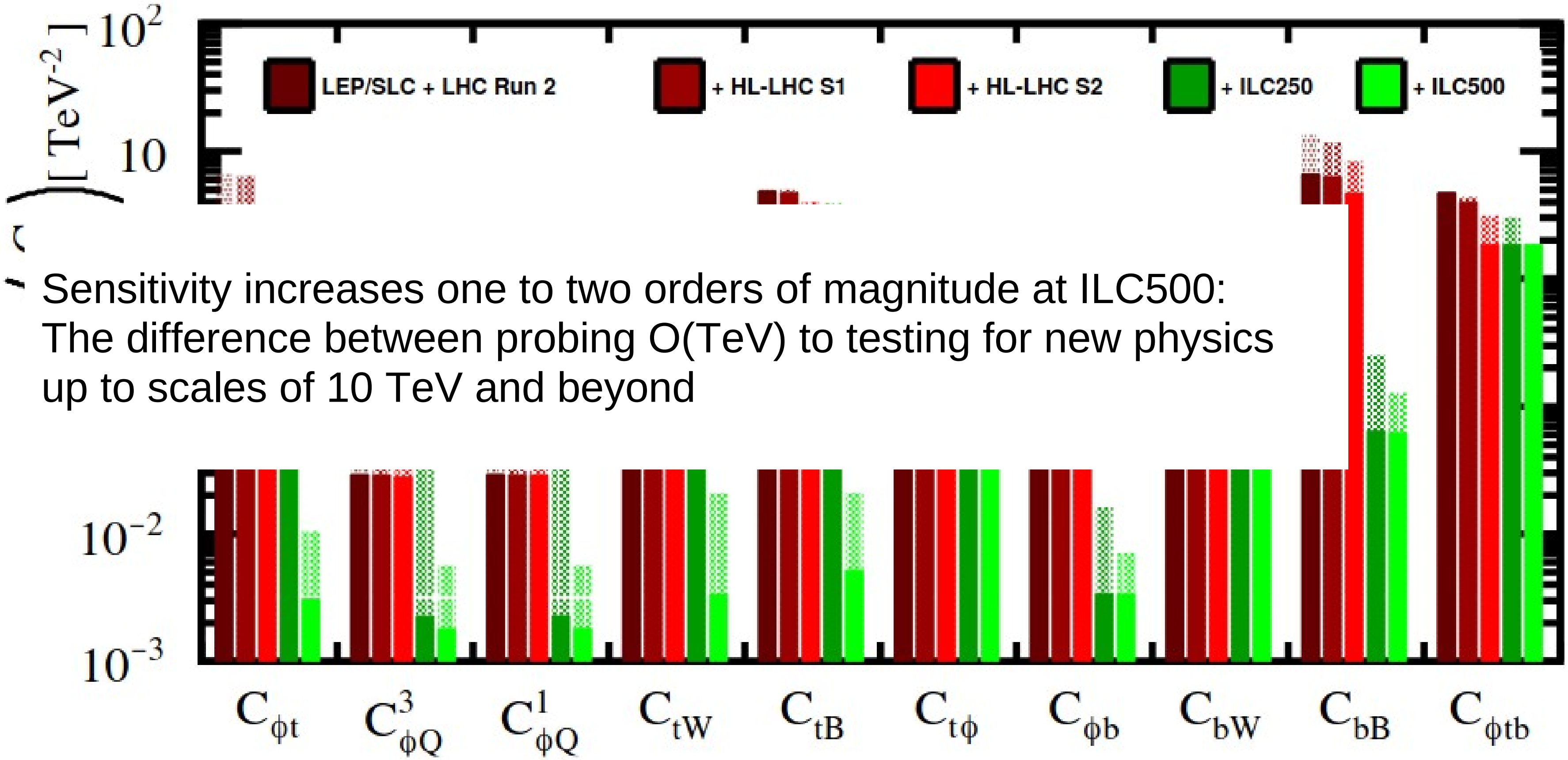
→ HepFit implementation with IFIC theory (A. Peñuelas, V. Miralles)

Comparison to prospects



HL-LHC S2: theory → 1/2, experiment ∝ 1/√L
ILC250: e+e- → bb (Irles et al., 1709,04289)
ILC500: e+e- → tt (1807.02441, 1807.02121, 1505.06020)

Comparison to prospects

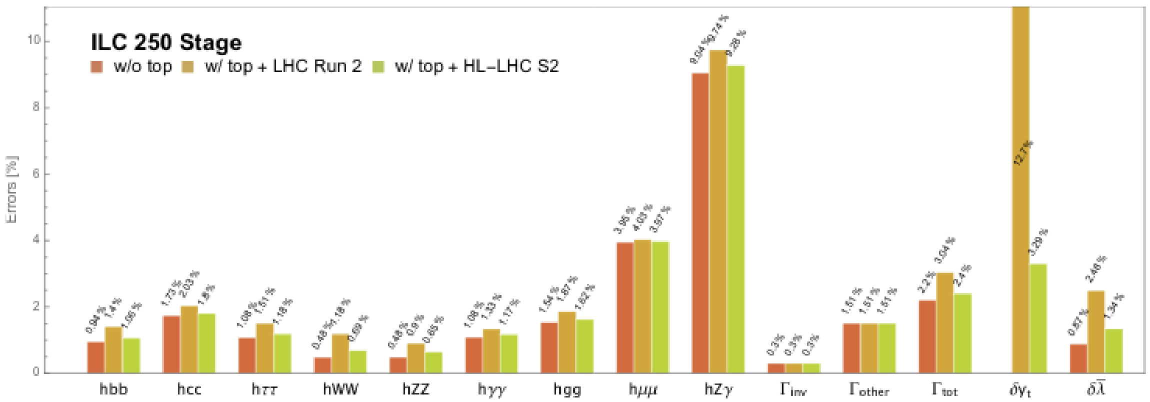


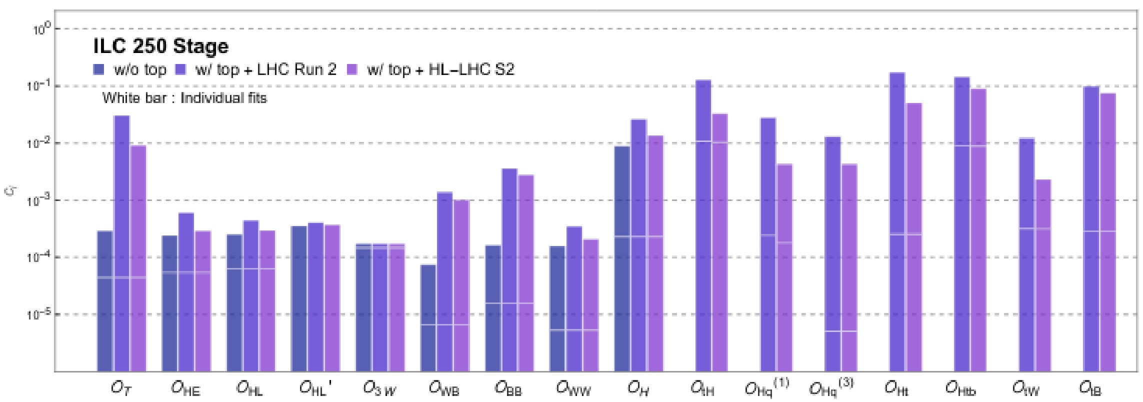
Sensitivity increases one to two orders of magnitude at ILC500:
The difference between probing O(TeV) to testing for new physics up to scales of 10 TeV and beyond

HL-LHC S2: theory → 1/2, experiment ∝ 1/√L
ILC250: e+e- → bb (Irles et al., 1709,04289)
ILC500: e+e- → tt (1807.02441, 1807.02121, 1505.06020)

Towards a fully global fit

Global top/Higgs/EW fit





Ongoing work: S. Jung, J. Lee, M. Perelló, J. Tian

Threat: “top” degrees of freedom can degrade “Higgs” fit considerably, even with HL-LHC S2 projection

Opportunity: indirect sensitivity to top EW operators (+Yukawa) yields tight single-parameter limits already at 250 GeV

HL-LHC + ILC250 + ILC550 (+ Z-pole) provides very robust bounds on extended Higgs/EW/top operator basis

Summary

Don't forget the top quark!

We need precise measurements of top quark properties – for their own sake and because of their interplay with Higgs/EW physics

Top quark mass: proposed new method to measure the top quark mass in the "standard" runs. Rigorous interpretation and competitive precision + bonus sensitivity to "running" of the top quark mass.

Top EW couplings: mature EFT analysis is becoming available to evaluate the impact of an e+e- collider in the top EW sector AND in a truly global SMEFT analysis. These results underline – once more - the importance of a complete programme with multiple center-of-mass energies

A new e+e- collider must explore beyond 250 GeV!!

top EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

Circular Collider 350+365

Sensitivity to four-fermion operators increases strongly with energy (see F. Riva, G. Durieux, this workshop)

ILC500+ ILC1000

Ultimate precision in global EFT fit requires a collider with two energy stages and polarization

CLIC380+ CLIC1500+ CLIC3000

Warning: versions with old luminosity

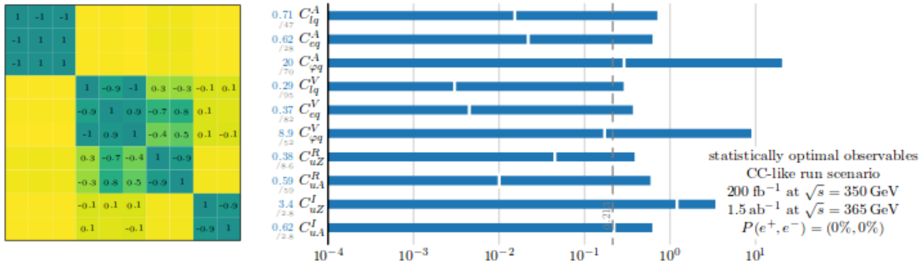


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

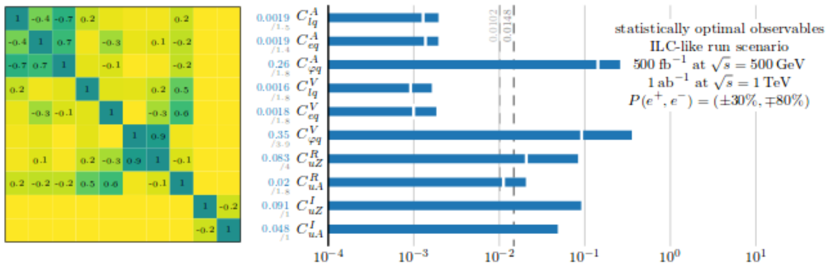


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

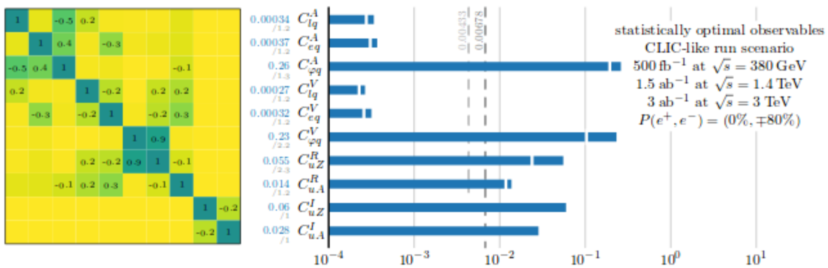


Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.